EMS Technologies
1725 Woodward Drive, Ottawa, ONT, K2C 0P9

NGST Alternative Instrument Preliminary Concepts
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	Names/Title	Signature	Date
Prepared by:	C. Evans / Optical Systems Engineer		
Prepared by:	B. MacKay / Mechanical Engineer		
Prepared by:	E. Greenberg / Materials Engineer		
Prepared by:	N. Rowlands / Space Science Manager		
Reviewed by:	A. Scott / Optical Systems Engineer		
Approved by:	G. Buttner / Director Space Science		

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1 Introduction

This report concerns an instrument concept study for the Next Generation Space Telescope undertaken by EMS Technologies in the period February/March 2001. The instrument concept studied was the Near Infrared Camera (NIRCAM), the main instrument on NGST as per the Ad-Hoc Science Working Group Recommendations. For the purposes of this study the overall NGST model assumed was the one in place at the end of 2000. This model was expressed in some detail on October 25th and 26th, 2000 in a design review of the Integrated Science Instrument Module (ISIM) concepts developed by NASA Goddard. Key assumptions for this concept study were that the Optical Telescope Assembly (OTA) had an 8m diameter, and was f/24. The architecture of the NIRCAM was assumed to be four modules each covering adjacent 2’ x 2’ fields of view. The main purpose of this study was to develop alternate optical and mechanical designs for the baseline NIRCAM concept and to assess manufacturability.

Early in 2001, the NGST Project Office reviewed the costs of the mission and decided to move to a 6 m to 7 m diameter primary mirror as the mission baseline. At this diameter a monolithic, as opposed to deployable, primary mirror could be considered. This change of scope has two very beneficial effects, the risk of an on orbit deployment is eliminated and ground testing is greatly simplified. At the time of writing the effects of this change of scope on the science instruments are not known.

Despite this change in the NGST project, many of the conclusions of this study are still applicable to the NGST NIRCAM, any other NGST instruments, and indeed to any high performance optical instrument which requires cooling to cryogenic temperatures.

2 NIRCAM Optical Design for NGST

The Near Infrared Camera (NIRCAM) for NGST relays a portion of the telescope field to a detector. In the process, the relay optics provide a stop-surface, suitable for filters and wavefront-sensing. This document examines some potential design solutions and compares them with one another and the published, *Yardstick* design.

2.1 General Requirements

The NIRCAM must provide at least the following functions:

- Relay a portion of the telescope field which corresponds to 2 _ 2 minutes of arc to either a 108 _ 108mm (27 μm pixels) or a 72 _ 72mm (18 μm pixels) detector. The sampling of the image in both cases is assumed to be 0.03” / pixel

- Operate over a waveband of 0.6 to 5μm.

- Provide an accessible pupil of sufficient correction for wavefront sensing and filtering.

2.2 Yardstick Design

Figure 2-1 shows the published NASA GSFC *Yardstick* design. It is a derivative of the Offner Relay and all the powered surfaces are spherical. The magnification is set up for 27μm pixels. Note that only one quadrant of the NGST Pyramid Mirror is shown.

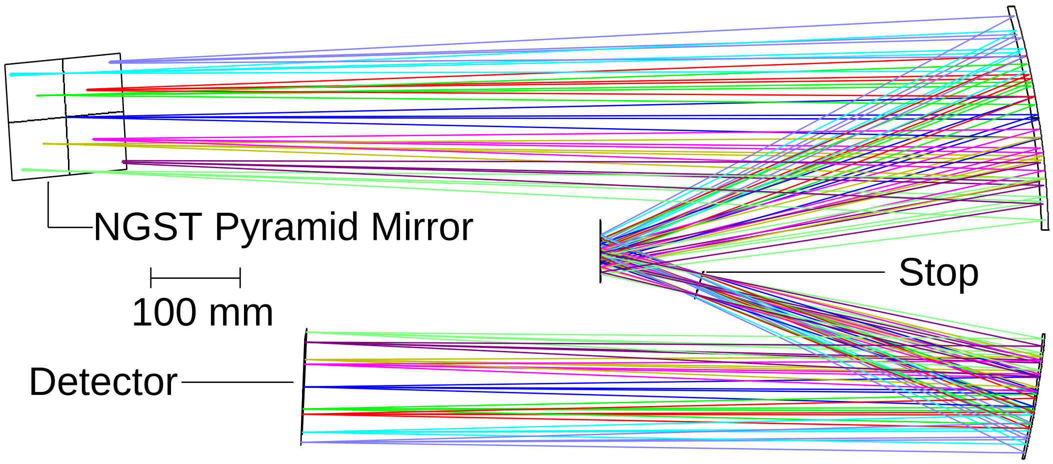

Figure 2-1 The Yardstick Design

This design has the considerable merit of simplicity. The spherical surfaces may be manufactured in many optical fabrication facilities and the alignment is straightforward. As a trade-off, the correction is modest at 0.6 μm and the pupil imagery is rather poor (see section 2.4).

2.3 Alternative NIRCAM Designs

Four NIRCAM optical designs have been produced for this document. There are two three-mirror designs – one for 27μm pixels and one for 18μm pixels. Similarly, there is a four-mirror design for each pixel size. The function of this design work is to explore the parameter space around the design requirements and explore some options for later work.

Two specific aims are:

- Improve the correction at 0.6μm
- Improve the pupil imagery
- Reduce the size of the NIRCAM mounting bench

As a trade-off, the design may use more complex fabrication technology.

2.3.1 Three Mirror Designs

Figure 2-2 shows a three-mirror design, set up for 18μm pixels. Figure 2-3 shows a similar design with 27μm pixels. All the powered surfaces are conic sections of revolution and have a common rotational axis.

The sizes are such that the mirrors can be machined on a large, diamond-turning lathe with an available diameter of 650mm. Diamond turning also offers the potential for a “plug and play” alignment scheme, using precision mechanical locations, machined into the mirrors during manufacture.

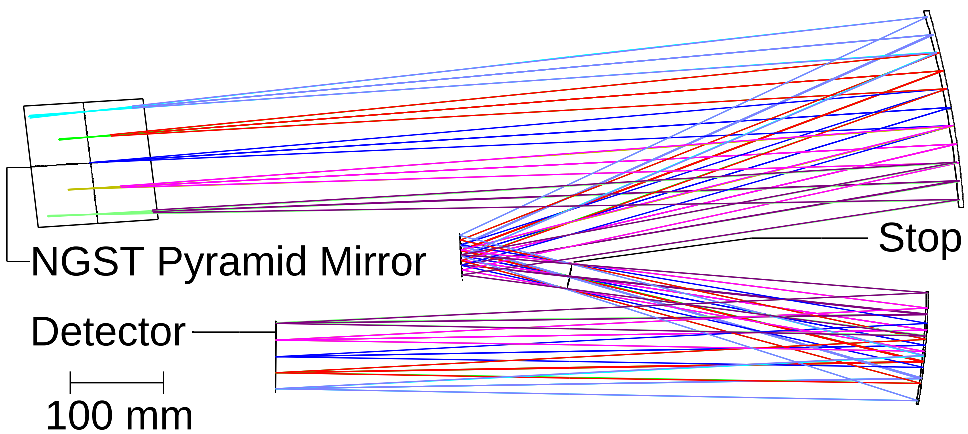

Figure 2-2 A Three Mirror Design with 18μm Pixels

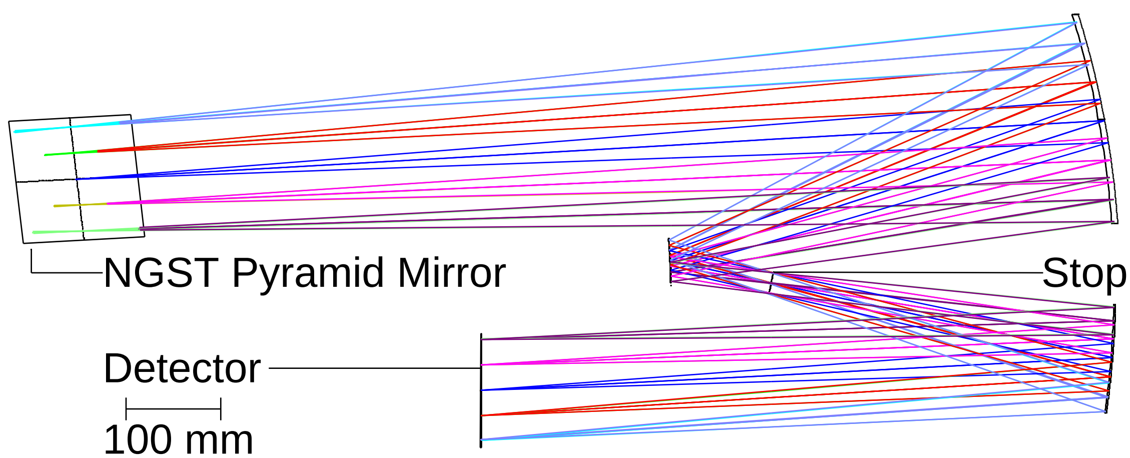

Figure 2-3 A Three-Mirror Camera with 27μm Pixels

2.3.2 Four-Mirror Designs

In the four-mirror designs, the powered surfaces comprise three conic sections and one asphere of rotation. The designs still maintain a common axis of rotation and their size is such that they remain compatible with diamond turning. Figure 2-4 shows the four mirror design with 18 μm pixels and Figure 2-5 shows the four mirror design with 27 μm pixels.

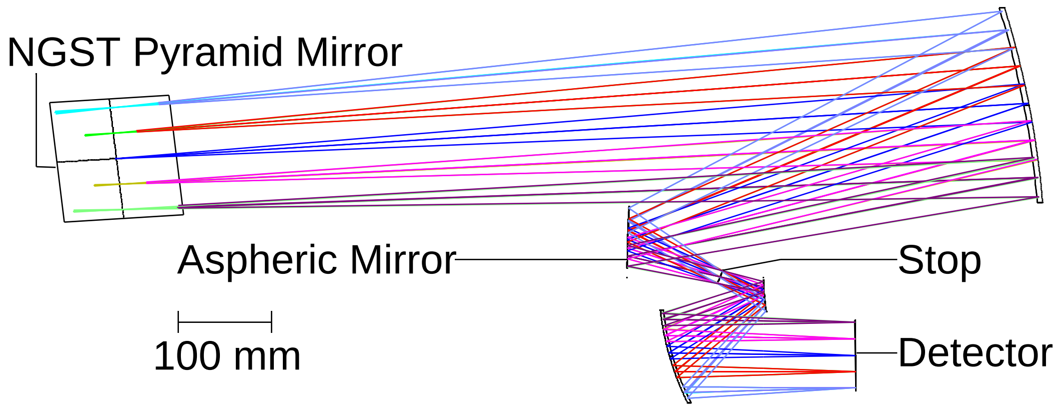

Figure 2-4 A Four-Mirror Design with 18μm Pixels

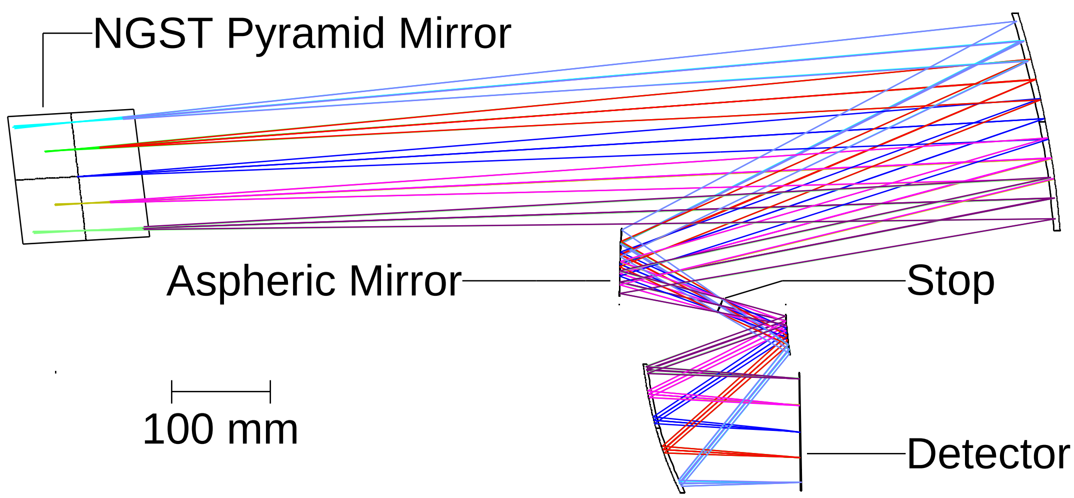

Figure 2-5 A Four-Mirror Design with 27μm Pixels

2.4 Comparison

We make some numerical comparisons between the designs in Table 2-1. The values in the table are calculated as follows:

- The RMS wavefront error indicates the range of values over the field of view.
- The pupil aberration is the ratio of the RMS spot diameter at the center of the pupil to the pupil diameter.
- The Bench size is the approximate length and breadth in millimeters required to accommodate the camera mirrors, the stop and the detector. The size excludes the NGST pyramid mirror.

Table 2-1 Numerical Comparisons of Camera Designs

	Yardstick	Three Mirror Design		Four Mirror Design	
Pixel Size	27μm	18μm	27μm	18μm	27μm
RMS Wave-front error @ λ=0.6μm	0.028 to 0.1 λ	0.024 to 0.044 λ	0.02 to 0.033 λ	0.01 to 0.03 λ	0.004 to 0.025 λ
Pupil Aberration	0.18	0.044	0.074	0.046	0.041
Bench Size (mm)	840_506	748_423	680_459	456_430	454_429

Note: The pupil aberration is expressed as the ratio of the spot size of the pupil image to the overall pupil diameter.

2.4.1 Pupil Imagery: Wavefront Sensing

In Table 2-1 we have expressed the pupil aberrations as a fraction of the pupil diameter because of the geometry associated with a wavefront sensing and correction scheme. The pupil aberrations, mapped onto the pupil surface with the deformable mirror actuator, should be small compared with the actuator spacing. Thus, the pupil aberration fractions listed in the table provide a measure of the number of controllable actuators across the pupil.

The total number of actuators scales as the reciprocal of this fraction squared. For example implementing some form of wavefront discrimination at the pupil of the Yardstick design would appear to only provide enough information to drive ~30 actuators. Since the NGST primary mirror will likely have hundreds of actuators controlling its surface figure, this pupil imagery would seem woefully inadequate. Even the 3 mirror 27 μm pixel design would provide information over ~180 sub-apertures. Given a 6 to 7 m primary mirror constructed from ~1 m sized hexagonal substrates each with a dozen or so actuators, then the total number of actuators on the primary mirror would be ~600. In order to control this number of actuators, the pupil image must be examined to the same level of detail in order to assess the contribution to the total wavefront of each sub aperture around each actuator. Only the four mirror designs provide sufficient image quality at the pupil.

2.4.2 Pupil Relief

Despite the added mirror, the four mirror designs also offer the most clearance around the pupil compared to the three mirror designs and the Yardstick design. This may be critical in terms of packaging. For example in the Yardstick design a large filter wheel design was developed that allowed the large diameter adjacent optical path to pass through the filter wheel mechanism, thus making this mechanism quite large. The four mirror designs presented here offer the best chance to minimize the structure needed for the filter wheel and for giving clearance to the possibly large sized optical components required for wavefront sensing.

Note that we find no significant savings in terms of instrument volume, and correspondingly mass, for the designs based on 18 μm pixels compared to 27 μm pixels. This is in agreement with statements by the GSFC Yardstick design team.

3 Optical Quality

For an optical surface with a uniform distribution of surface roughness scales, the total integrated scatter is related simply to the root mean squared surface roughness (σ) as in:

$$TIS = (4 \pi \sigma / \lambda)^2$$

Figure 3-1 shows this total integrated scatter as a function of surface roughness for the 0.6 to 5 μm wavelength range.

Ultimately the surface roughness requirements of the NIRCAM need to be determined via consideration of the types of observations to be made, but in the meantime a rough estimate of the requirements can be made. For example, the surface roughness limit of net shape diamond turning in aluminum for mirrors as large as the NIRCAM optics is on the order of 10 nm. From Figure 3-1, such a roughness level would result in almost 5% scattered light at 0.6 μm from each NIRCAM mirror. This much scattered light would not only impact the light distribution at the detector but would actually reduce the throughput of the instrument. The only solution is to improve the surface roughness by polishing. This can be done either in nickel coated metal mirrors or on glass substrates. Given the requirement for operation of the instrument at room temperature and at 30K to 60K, it is strongly preferred to make the instrument structure and the optical component substrates from the same material; nominally a metal for ease of fabrication.

The issue with nickel coated mirrors is with deformation on cooldown due to the different co-efficients of thermal expansion of nickel and the metal mirror substrate (usually an aluminum or beryllium alloy). Nickel is a stiff and strong material and even the thin (~10 μm) coating required for post-polishing is sufficient to deform a large thick (few cm) aluminum mirror when the temperature changes by tens of degrees C. However with careful design and modeling it is possible to fabricate nickel coated metal optics which can be cooled to cryogenic temperatures without significant optical figure changes (see section 4).

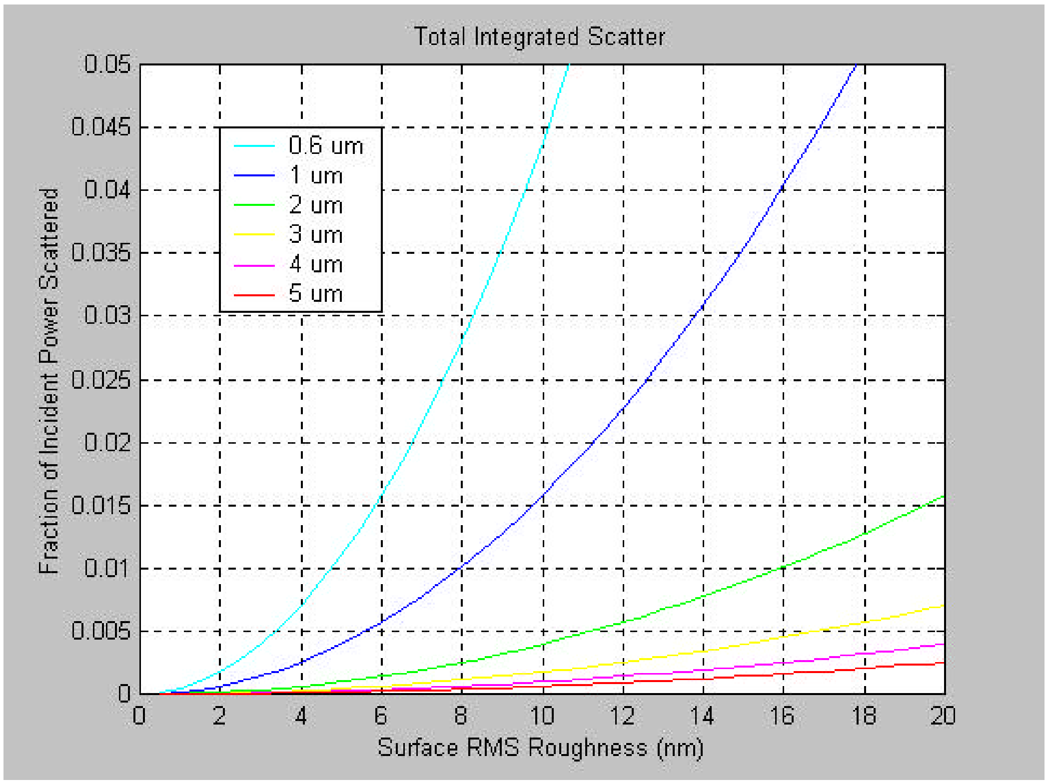

Figure 3-1 Total Integrated Scatter vs RMS Surface Roughness

As an alternative to post-polishing, a technique which has been reported to achieve very low (<3 nm) surface roughness on net shape diamond turned mirrors has been developed by AlumiPlate Corporation (http://www.alumiplate.com/html/body_optics.html) of Minneapolis, Minnesota. To use this process, an aluminum alloy mirror is first diamond turned to the approximate shape, then plated with 20 to 40 nm of pure aluminum and then diamond turned to the final shape with a fresh diamond tool. This results in a better surface than from diamond turning alone. This process has been reported to produce extremely stable mirrors for cryogenic applications because the high purity aluminum has such a close CTE match to the aluminum alloy substrate. However, Raytheon ELCAN's experience with this process has indicated that the resulting surfaces are exceedingly soft and almost impossible to clean. Given that any NGST instrument will progress through many levels of integration activities, a mirror surface that is difficult to clean is not a good approach.

Another possibility, although a potentially more problematic one, is the post-polishing of bare diamond turned aluminum surfaces. Such polishing is a surface touch-up technique only; no tuning of the surface figure is possible since this would require the removal of too much material. Great care must be taken to avoid scratching the soft aluminum surface (reference discussion with Jeff Wimperis formerly of Lumonics Optics Group). This technique is not commonly done and would require extensive trials before we could be certain that the surface roughness of the large NIRCAM mirrors could be improved by this method.

4 Cryogenic Optics

In order to evaluate the potential use of nickel-plated mirrors, a simple model of the structural deformation experienced by such a mirror fabricated at room temperature and cooled down to 80K, was developed. Two materials were used for comparison; an aluminum alloy (6061-T6) and a beryllium alloy (AlBeMet, a composite material developed by Brush Wellman, Elmore, Ohio). Additional discussion of material properties and selection criteria can be found in section 5.0.

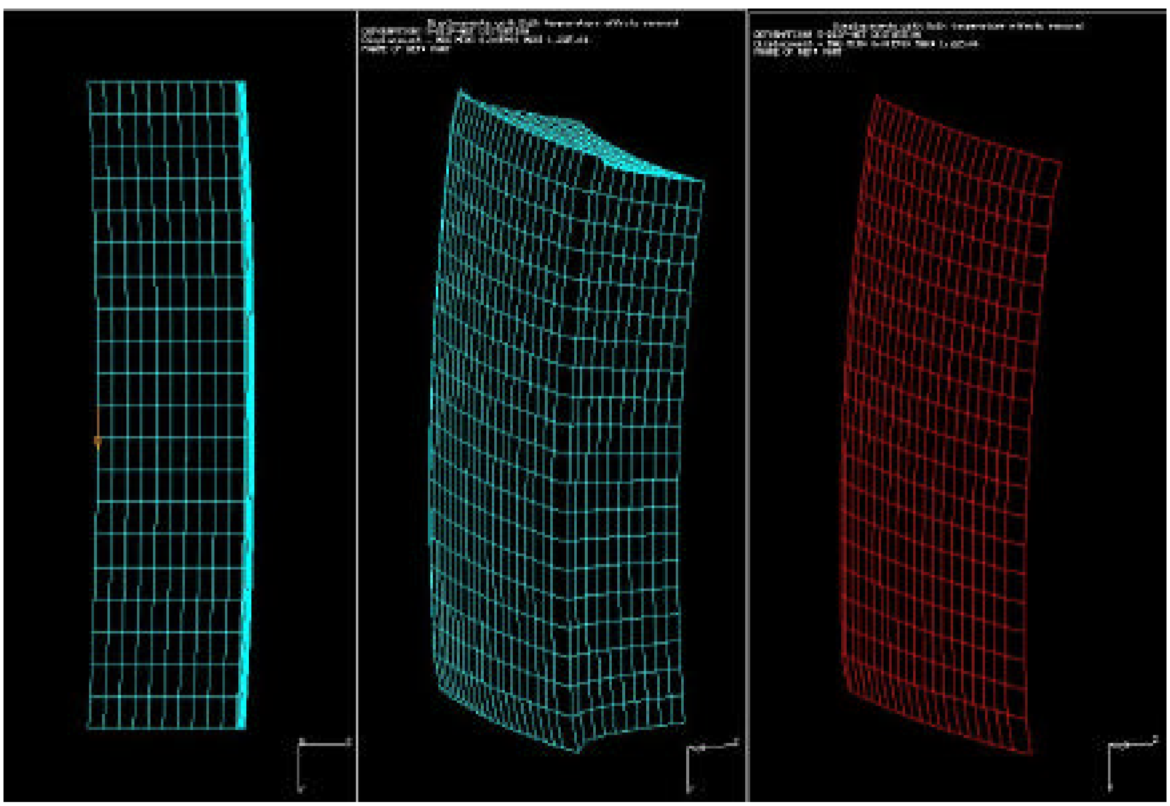

Figure 4-1 Solid aluminum mirror, 220 mm square, 50 mm thick with a 13 μm Ni plating over the entire part. The right hand side picture in red shows the surface distortions in the finite element mesh magnified by a factor of 10,000 compared to the size of the mirror when the mirror was cooled to 80 K.

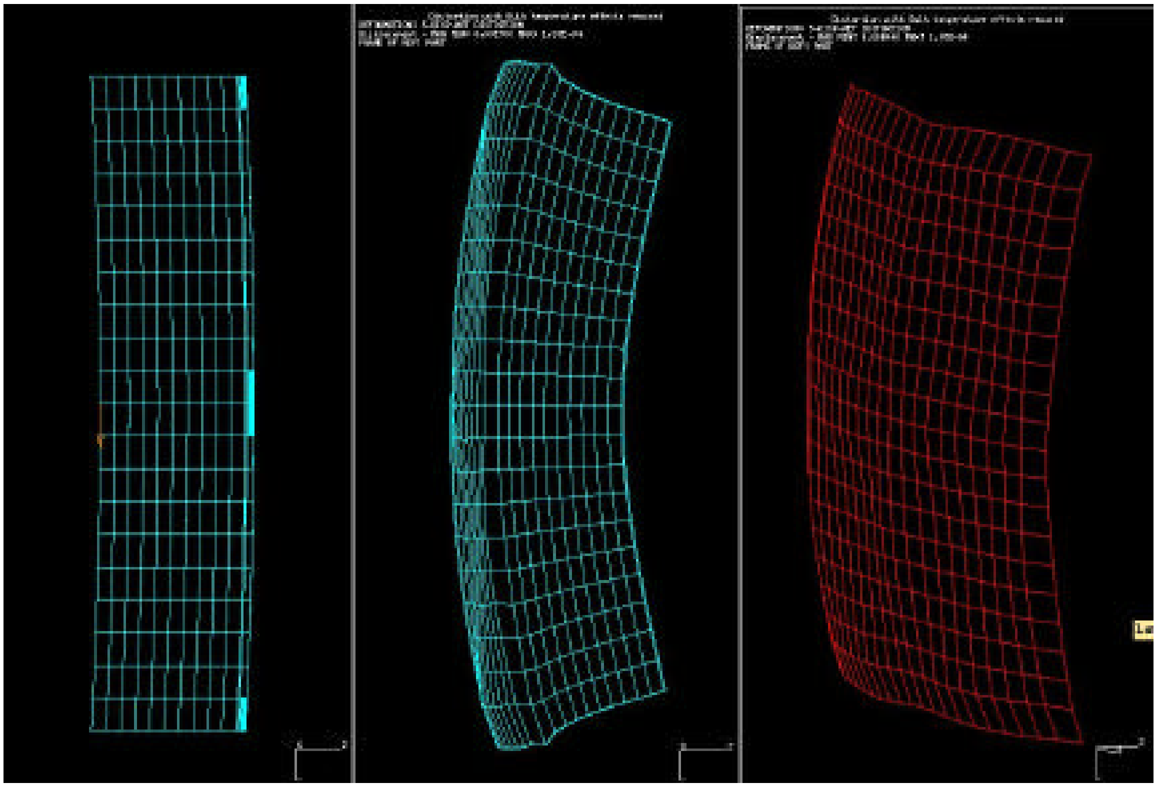

Figure 4-2 Aluminum mirror light weighted via four square pockets in the rear. The overall mirror is 220 mm square, 50 mm thick with a 13 μm Ni plate over the entire part. The right hand side picture in red shows the surface distortions in the finite element mesh magnified by a factor of 10,000 compared to the size of the mirror when the mirror was cooled to 80 K. The cruciform structure of the ribs remaining after light weighting are obvious, these distortions are problematic because they produce mid-form wavefront errors which can significantly distort the point spread function.

For each material two cases were initially examined, a solid mirror and a mirror lightweighted with four pockets at the rear. In all instances the largest mirror in the four mirror designs was used, a 220 mm square mirror which is a paraboloid 180 mm off axis. As modeled, the mirror was 50 mm thick and entirely plated with 13 μm thick nickel. The results are shown in Figures 4-1 and 4-2, which are pictures of the Finite Element Analysis Mesh across the optical surface of the mirrors.

The stresses observed in the nickel coating were high, on the order of 75 ksi. Pure nickel has a tensile strength of between 16 and 90 ksi. On a cryogenic mirror this size; cracking of the nickel plating is thus a serious concern. Some experimentation in nickel-plating techniques may be required in order to produce a surface which will survive multiple cool-downs.

Table 4-1 Maximum Surface Distortions of the Mirrors

Max Mirror Distortions	Solid Form	Light weighted (4 pockets)	Light weighted (64 pockets)
Aluminum / Nickel	- 0.11 μm	3.8 μm	1.0 μm
AlBeMet / Nickel	0.004 μm	- 0.14 μm	

Note: Negative values imply the mirror tends to become more curved. A positive distortion implies the mirror flattens out.

As expected the light weighted mirror distortions are substantially worse, as are the distortions of the aluminum mirrors. The coefficient of thermal expansion of aluminum is substantially greater than that of nickel, while the CTE of AlBeMet is only slightly smaller than that of nickel, so the distortions in the AlBeMet cases are much smaller. In all cases the nickel plating was applied to both the front (optical) and rear surfaces. In the light weighted case the nickel plating was applied only to the back of the pocketed areas. As perhaps could be expected, the simple light weighting with the large pocketed areas, resulted in the largest distortions.

In order for the thermal distortions of the mirrors to result in negligible wavefront error in the NIRCAM imaging system the overall wavefront error must be less than 0.074 waves at 2 μm (the diffraction limited requirement). Given that there are four large powered mirrors within the NIRCAM, this image quality requirement translates into surface distortions which are less than ~0.04 μm on each mirror. The only case which satisfies this condition in Table 4-1 is the solid AlBeMet case. Since light weighting is very desirable, methods of reducing this distortion should be considered. There are two principle methods.

First, after plating and testing, a mirror can be “cryogenically figured”. Since the distortion resulting from thermal distortion is usually deterministic, an interferometric map of the mirror cooled to operating temperature can be made and used to polish in the inverse of this figure at room temperature. In this fashion the mirror achieves near ideal figure at operating temperature. In the extreme case the final diamond turning fabrication step could be adjusted to obtain the desired figure. In the case of the light weighted aluminum mirror, even this is problematic since the nickel-plating itself is only ~ 3 times the distortion to be polished out. It is clear that detailed modeling, such as that presented here, is required for a given light weighed design before fabrication, so that the amount of distortion and hence the thickness of nickel plating required, can be pre-determined.

Secondly, since detailed distortion modeling is possible, various light weighting designs can be iterated until the distortion is minimized to acceptable levels. The results for the solid AlBeMet mirror substrate indicate that there are potentially less extreme light weighting designs, for example many smaller pockets, which will still produce minimal distortion at operational temperatures. One case was analyzed for comparison and this was an aluminum mirror with 64 circular pockets each 17.8 mm in diameter machined into the rear for weight relief. The resulting cryogenic distortion was a factor of four smaller than in the case of the coarser weight relieving. While this form of light weighting is still not sufficient for the aluminum substrate, an AlBeMet mirror light weighted in this fashion would likely meet the requirement.

Given that the distortion of even the solid aluminum mirror is beyond the allowable limits of the NIRCAM, then it would appear that cryogenic figuring will be a requirement if aluminum mirror substrates are used. This is an important conclusion, because cryogenic figuring will significantly increase the fabrication costs of the NIRCAM optics.

5 Structural Design

A study was made of two methods of fabricating the NIRCAM optical assembly. Given the very low operating temperatures of these optics it is considered very important to ensure that materials used within the structure are compatible with each other. Two materials were considered; a standard aluminum alloy and AlBeMet. The latter material, available from Brush-Wellman (Elmore, Ohio), has a high absolute stiffness and very low density. This alloy has a coefficient of thermal expansion similar to that of stainless steels.

Ideally an optical frame with no or few mechanical joints would lead to a more optically stable design. The initial approach that was taken attempted to create a monolithic optical frame that would have been created from a solid block of material. This proved to be unworkable (see section 5.2) so a plane and strut design was developed and the results are discussed in section 5.3. First, section 5.1 deals with the material selection issues.

5.1 Structural Material Selection

The ideal material for the NIRCAM structure is one with the largest possible specific modulus, or ratio of elastic modulus to density, resulting in the lightest, stiffest structure possible. The components which the NIRCAM structure must support will not be significantly more massive than the structure which supports them. The large spacing of the optical components compared to their size precludes this case. In such an instance the specific strength of the structural material is less important than the specific modulus.

Table 5-1 clearly indicates that beryllium and its alloys are the optimum materials. There are however, drawbacks to beryllium and its alloys in that any fine particles resulting from machining operations can be a significant health hazard. This hazard can be controlled with vapor extraction equipment installed at the machining sites and appropriate operator safety equipment. Many space qualified optical systems in beryllium have been successfully developed and flown.

Fabricating the NIRCAM optical components and structure from the same material is a very significant advantage in terms of reducing design complexity and testing complexity. All aluminum and all beryllium optics and structures have been used successfully for cryogenic instruments. However, beryllium does have a disadvantage in terms of a structural material in that it cannot be joined (welded) easily. Bolted interfaces can be used but because they are less deterministic in terms of structural modeling they are usually avoided. Adhesive joints can also be considered, however, the cryogenic operation and differential CTE, makes their use problematic as well. In this instance AlBeMet is a more convenient material because it can be joined (welded) more readily. While it is conceivable to use an AlBeMet structure with beryllium optical components, the optical components will be nickel-plated. Thus it is also possible to consider AlBeMet optical components which are nickel-plated.